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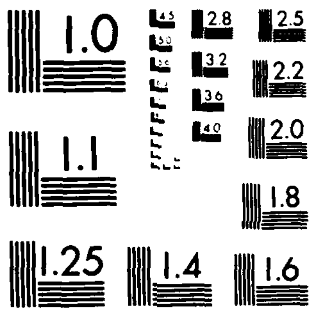

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A brief summary of the highlights of the International Conference on Metastable and Modulated Semiconductor Structures is provided. The report emphasizes (i) the theme of the conference and the systematic coverage of related topics (ii) a technical discussion of the papers presented, their inter-relationship and future prospects.

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SCIENTIFIC REPORT ON THE INTERNATIONAL CONFERENCE ON METASTABLE AND MODULATED SEMICONDUCTOR STRUCTURES (MMSS)

The International MMSS Conference was held from December 6-10, 1982 at the Huntington-Sheraton Hotel in Pasadena, California. It was organized by an international committee headed by the co-chairmen, Dr. A. Madhukar of the University of Southern California, Los Angeles and Dr. F. J. Grunthaner of the Jet Propulsion Laboratory, Pasadena.

The objective of the conference was to bring together practitioners of a wide variety of techniques for the fabrication, characterization and study of the newly emerging field of metastable and modulated semiconductor phases and structures, with the express purpose of promoting cross fertilization of ideas. It was felt that this aim was best achieved by restricting the conference size to between 100 and 125 participants, structuring a program with heavy emphasis on theme setting invited talks, and providing for ample time for discussions, both during and after the sessions. To enhance this aim, only morning and evening sessions were held. A new format employed to further this objective was to require all invited and contributed papers to be also presented as posters which were displayed throughout the conference. The feedback from the participants has indicated that this format was highly appreciated and found to be remarkably effective in promoting critical discussions.

The scientific content of the program was divided into several categories and chronologically arranged to emphasize a systematic development of the subject and the central issues. After an opening session containing two conference theme talks by Dr. Leo Esaki and Prof. P. Duwez on the subject of modulated semiconductor structures and creation of metastable phases, respectively, the regular sessions began with fabrication techniques for metastable phases followed by the new techniques evolving for fabrication of modulated semiconductor structures. These sessions emphasized such techniques as rf-sputtering, metal-organic chemical vapour deposition (MO-CVD), molecular beam epitaxy (MBE), liquid phase epitaxy (LPE), and their new and novel variations. This was followed by two sessions focussing upon the growth mechanisms, and the particular role of growth kinetics and thermodynamics in offering possible ways of creating new and novel metastable phases and structures. Although the tetrahedrally bonded semiconductor combinations found a heavy representation reflecting the large activity around the globe, special place was given to a discussion of the even newer class of metastable systems and compositionally modulated structures involving lattice matched and non-lattice matched semiconductor-dielectric combinations (e.g. $Si/(Ca,Sr)F_2(100)$) and silicon-transition metal silicide combinations. Finally, the subject of doping-modulated systems (the so called nipi structures) and the creation of metastable doping

profiles via Q-switched laser treatment and the kinetics of such doping processes was critically evaluated.

The conference then proceeded to an examination of the variety of characterization techniques, starting with structural characterization (such as electron microscopy, x-ray diffraction, Rutherford back scattering) with a heavy emphasis on the use of these techniques and their requirements for study of thin (submicron) layers and their interfacial characteristics. Next, the subject of chemical characterization (via techniques such as x-ray photoemission, Auger electron spectroscopy, etc.) was critically examined, before moving on to optical characterization via techniques such as spectroscopic ellipsometry and photoluminescence.

A new and important feature of these sessions on the characterization techniques was the heavy emphasis on the relationship between the information so obtained and the growth mechanism and growth kinetics

The conference next moved on to a discussion of the electronic consequences of the growth mechanism and the resulting structural and chemical characteristics of the systems. The electronic structure of the strained layer superlattices was emphasized. Next, the transport, optical and magneto-optical properties of the quasi-two-dimensionally confined space charge layers in single interface heterojunctions, isolated quantum wells and superlattice structures was discussed. These sessions included some basic aspects of such space charge layer properties, as well as the more applied aspects of relevance to a variety of high speed and/or high frequency devices. Transport under high d.c. fields and the associated real-space charge transfer and hot electron effects reflect an example of such topics.

The final session of the conference focussed on the exploitation of such structures, their characteristics and the properties of the space charge layers realized in them for a variety of new and novel devices. Emphasis was laid on, for example, the high electron mobility transistor (HEMT) being extensively investigated in the GaAs/AlGaAs system. Considerable discussion was focussed on the high-speed, high-frequency device possibilities. yet another example was manifested in the discussion of the multilayer avalanche diodes and infrared detectors based upon electron emission from multiple quantum well structures.

The specific highlights of the papers presented at the conference, their interrelationship and the future prospects were summarized in the attached paper written by the co-chairmen for this express purpose. For such details, the reader is thus referred to F. J. Grunthaner and A. Madhukar, Proceedings of the International MMSS Conference, J. Vac. Sci. Tech. B1, 462 (1983).

Growth, characterization, and properties of metastable and modulated semiconductor structures: Prospects for future studies

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The general field of preparation and study of metastable and modulated semiconductor structures has progressed rapidly in recent years. This short overview offers an assessment of the progress and current understanding in the areas of fabrication, characterization, and utilization of these new material systems. The discussion includes the more prominent growth techniques, theoretical and experimental analysis of growth kinetics, and an overview of structural, chemical, electronic, and optical characterization. The probable application of these structures for the technological development of new device structures and concepts is considered. The discussion particularly emphasizes the prospects for future studies in view of the specific current understanding.

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I. INTRODUCTION

The creation and study of metastable and modulated semiconductor structures is a relatively new subject which has been motivated by the needs of semiconductor technology and has witnessed rapid increase in effort over the past few years. The scientific community involved in these efforts represents an unusual breadth of particular specialties and interests consistent with the interdisciplinary nature of the problem. This community includes the disciplines of materials science and crystal growth, surface scientists, experts on materials characterization through a variety of electrical, optical, and electron spectroscopic techniques, theoretical and experimental solid state physicist, and device physicists and engineers who provide the technological driving force for the collective effort. In the following, we have attempted to review some of the key scientific and technological aspects of the creation, characterization, understanding and utilization of these new material systems. Our discussion first focuses on the general notion of metastability and modulated structures. We then provide a comparative discussion of the more prominent techniques being employed for the synthesis of such materials and structures. This is followed by theoretical and experimental observations on growth mechanisms, and structural, chemical, electronic, and optical characterization. Finally, we consider the implications of these materials for the technological development of new device structures and concepts. The emphasis here is on the basic ideas exemplified in certain specific material systems investigated to date, rather then the material systems themselves. Consequently, omission of reference to the variety of specific systems and studies is not a reflection of their lack of importance for the specific purpose for which such studies were, and may continue to be, made.

The International Conference on Metastable and Modulated Semiconductor Structures (MMSS) placed a heavy emphasis on what we believe to be the three pressing issues relating to metastable and single or multilayered semiconductor structures. These are (i) the dynamics and kinetics of the growth and growth mechanisms of metastable single and multi-interface semiconductor structures; (ii) their dependence upon the growth parameters and conditions, particularly for growth techniques involving or offering far-from-equilibrium conditions for realization of metastable phases, and (iii) correlation of (i) and (ii) with the properties of the resulting system.

Traditionally the term phase (within the context of solid state) has come to represent a state characterized by its composition and structure. The external conditions such as temperature, pressure, concentration, etc., define the regime of thermodynamic equilibrium conditions within which the phase is said to be stable. Away from such a regime, the phase becomes "unstable" and will transform to the most favorable "stable" phase accessable under the given conditions. If this rate of transformation is very slow, the parent phase is referred to as being metastable. Clearly then, the conditions of metastability are inherently tied to the kinetics of the system under prescribed conditions, rather than the thermodynamics. Viewed from a system-free energy-configuration coordinate-diagram point of view, the significant quantity is thus the activation barrier for transformation from one phase to another, rather than the energy difference of the two. Generally, low mobilities of the species involved in the system and a high activation barrier for transformation to the stable phase (under the given conditions) are needed for stabilization of the metastable phase. The synthesis of metastable phase(s) is thus, by definition, an attempt to create a phase outside the region of the thermodynamic stability embodied in conventional phase diagrams. For growth from the vapor phase, stabilization of a metastable phase generally requires high supersaturation (i.e., far from thermodynamic

equilibrium conditions). When more than one metastable phase is possible, the one with the highest nucleation frequency under the given growth condition will form first. The control of the kinetics of growth is thus of central importance to creation of metastable phases.

The modulated semiconductor structures[1] may be of two kinds—one in which alternating thin films of two or more materials are sequentially deposited along a prechosen growth direction, and another in which alternate *n* and *p* doping may be introduced within the same material. The former may be referred to as compositional modulation and the latter as doping modulation. While the former leads to modification of the electronic states in the wave vector space (*k* space), the latter modulates the electronic states in real space. Many, if not all, of the modulated structures of both kinds involve some aspect of metastability, and often in a significant way.

II. SYNTHESIS TECHNIQUES

One of the more significant developments in recent years is the exploitation of the growth kinetics, often under far-from-equilibrium conditions, for the creation of new metastable phases and synthesis of new single or multi-interface device structures. The most promising growth methods are variants of vapor phase epitaxy since this approach is consistent with lower growth temperatures and far-from-equilibrium conditions. Molecular beam epitaxy (MBE),[2] metal-organic chemical vapor deposition (MO-CVD),[3] and rf sputter deposition[4] each differ substantially in experimental methodology and in the dynamics which characterize the vapor/solid growth interface, yet the quality of structures fabricated using these techniques are surprisingly similar. This similarity is intriguing for both scientific reasons and pragmatic considerations, such as the differences in the required capital investment for these techniques. Although MBE is often cited as the method of choice for the fabrication of multilayer structures, the characteristics of MO-CVD grown single films have been essentially identical[5] to those grown by MBE. High quality multilayer structures have also been grown[5–7] by MO-CVD. While in comparison to MBE the technique of MO-CVD offers higher growth rates, additional degree of freedom afforded by carrier gas interactions, and a greater ease of handling phosphorus chemistry, the interfacial width for both A on B and B on A growth seems to be greater than that achieved in MBE. Moreover, the opportunities for "*in situ*" monitoring of the interfacial growth front appear to be comparatively limited. The good quality of films achieved by rf sputter deposition methods and their sensitivity to the ion and electron energies involved in the experiment are quite suggestive of the usefulness of external manipulation of the growth interface in other techniques such as MBE.

Many of the key opportunities intrinsic to the MBE technique reduce to the low growth temperatures and rates employed along with the accessibility of the growth interface for extensive study and characterization using "*in situ*" surface sensitive techniques such as reflection high energy electron diffraction,[8,9] electron and photon stimulated electron spectroscopies,[10,11] and photon spectroscopies (e.g., spectroscopic ellipsometry[12]). The ability to carry out unambiguous *in situ* characterization studies, preferably during growth, is of central importance for understanding the nature and relative significance of the kinetic processes which control the structural and chemical nature of the grown system. The interrelationship of the growth kinetics and the structural and chemical nature of the dynamic growth front, the choice of substrate and source materials (defining the vapor phase species), growth temperature, and other growth conditions will become apparent in our discussion of such issues in the later sections.

Recently, MBE techniques have been extended to the growth of semiconductor–insulator and semiconductor–metal (or semimetal) single and multiple interface structures.[13–16] This is a significant development of potential importance to a variety of device structures and architectures.

Future work will undoubtedly focus on a number of issues noted above. There are, however, efforts, generally at too early a stage to have been represented at this MMSS conference, which are breaking new ground and introducing new ideas for fabrication of metastable and modulated semiconductor structures. For instance, the use of appropriate laser beams for controlled modification of surface kinetics on a local spatial scale to effect fabrication of metastable epitaxial thin film phases is being attempted.[17] This naturally brings in an added dimension, offering opportunities for both the fundamental theoretical and experimental studies of external beam–solid surface interactions in the context of crystal growth, as well as the development of experimental techniques to achieve the desired objective.

III. METASTABLE FILMS

In this section we provide a brief account of the two types of metastable epitaxial thin films realized to date. For simple alloy films, the significance of the kinetics of growth are amply, reflected in the successful creation of metastable alloy phases of thermodynamically immiscible systems such as $(GaAs)_{1-x}Ge_{2x}$ and $(InSb)_{1-x}Bi_{2x}$ via rf sputtering.[4] Specific kinetic limitations are often operative in different techniques for synthesis of the same system as exemplified by the difficulties encountered with segregation of Bi in the MBE growth[13] of $(InSb)_{1-x}Bi_{2x}$. Another aspect of metastability is manifested in the epitaxial strain induced stabilization of structural phases such as the realization of the semiconducting α-Sn phase in thin film form on InSb(100) and CdTe(100) substrates.[13] Epitaxy induced stabilization of particular phases has also been reported for liqud phase epitaxial growth.[18] Another relatively new development[13] is the fabrication of metastable fluoride alloy thin films at compositions inaccessable to normal near thermodynamic equilibrium crystal growth techniques. This offers the possibility of fabricating and studying dielectric films nearly lattice matched to group IV and several III–V semiconductors and eventually even fabricating modulated structures of such component systems. Further work on these systems and the usefulness of these basic ideas for other material systems can be expected in the very near future.

The MBE growth of an $Al_xGa_{1-x}As$ alloy film on (110)GaAs has revealed[19] the unexpected occurrence of qua-

siperiodic fluctuation in the Al concentration along the growth direction, possibly corresponding to formation of a kinetically controlled immiscible metastable region—one not found in LPE growth. Much further work on this system needs to be carried out for different growth conditions to provide a meaningful framework within which some basic and fundamental aspects of the surface orientation dependent kinetics and growth of compound semiconductor can be examined.

IV. MODULATED STRUCTURES

Compositionally modulated structures have, to date, been realized with semiconductor–semiconductor, semiconductor–dielectric, and semiconductor–semimetal combinations. Prominent examples of good quality systems in these categories are GaAs–AlGaAs(100),[2] InAs–GaSb(100),[2] Ge–GaAs(100),[20,21] and Ge–GaAs(110),[20,21] Si/(Ca, Sr)F_2(100),[14] Si/(Ca, Sr)F_2(111),[14] CdTe–HgTe(100),[22] and Si/(Co, Ni)Si_2(111).[14] In addition, compositionally modulated structures involving three material components have recently been realized via MBE growth of InAs–GaSb–AlSb(100) system. The most extensively investigated system at present appears to be the MO-CVD and MBE grown GaAs–AlGaAs(100) system. It does not exhibit the compositional fluctuation noted in the previous section for the [110] MBE growth. The interfacial quality of the MBE grown [100] GaAs–AlGaAs system, however, does show sensitivity to several growth parameters as well as to the background pressures of contaminants such as oxygen.[19] The observed dependence of the interface roughness on the growth parameters[24] (e.g., substrate temperature), if intrinsic, emphasizes the need for and an opportunity to seek a deeper understanding of the role of kinetics in growth from the vapor phase in general, and MBE growth in particular. We will further comment on this issue in the next section. The deposition of Ge on GaAs(100) and (110) surfaces has revealed the occurrence of replacement reactions involving exchange between Ge and As, once the Ge coverage exceeds the surface As concentration.[20,25] This results in the formation of the $GeAs_x$ compound at the surface. On the other hand, such replacement reactions are not observed in the deposition of GaAs on Ge substrates.

The semiconductor–semimetal form of modulated structures involving CdTe–HgTe have very recently been realized[22] via MBE. This is a significant step for this material system of much potential use for infrared device technology, even though much characterization work still needs to be carried out. Undoubtedly this work will be vigorously pursued by several investigators. Finally, realization[14] of epitaxially grown modulated structures of Si/$CoSi_2$(111) and Si/$NiSi_2$(111) of high crystalline quality via MBE opens up a new class of silicon based systems for further investigations.

The synthesis of modulated structures involving semiconductor–dielectric combinations is of considerable significance to a wide variety of problems. Although the technological use of such systems ultimately leading to three-dimensional architecture will require many related developments and thus may not be foreseeable in the immediate future, the successful fabrication[14] of Si/(Ca, Sr)F_2(100) and Si/(Ca, Sr)F_2(111) is a most significant step in the right direction. This should prove to be an area of intense research interest in the immediate future.

The study of the effect of the degree of substrate-overlayer lattice mismatch on the equilibrium behavior of epitaxially grown films has a long history. Guidelines for equilibrium behavior are provided by the oversimplified theories[26] of Frank and van-der Merwe, and others.[27] The idea of the accommodation of lattice misfit via homogeneous strain below a certain critical thickness of the overlayer embodied in these theories has been extended to multilayer systems and was exploited nearly a decade ago in the pioneering work[28] of Blakeselee and Matthews on the fabrication of GaAs/$GaAs_{0.5}P_{0.5}$ strained layer superlattices via vapor phase transport. Very recently, such strained layer superlattices have been fabricated via MO-CVD[7] as well as MBE[29] and offer a certain useful flexibility in achieving independent control of the lattice constant and the band gap over a range which depends upon the material components involved.[30]

We conclude this section by noting that the doping superlattices, contained in the original propositions[1] of Esaki's and Tsu, and extensively investigated[31] theoretically by Dohler, have been realized in GaAs. Such studies in other systems are thus likely to follow suit and we may finally look forward to the emergence of this class of modulated structures.

V. KINETIC ASPECTS OF GROWTH AND DOPING

As observed earlier, the successful growth of high quality metastable and modulated semiconductor structures rests upon control and manipulation of the growth kinetics. Any attempt, however, to discuss this aspect in general terms is unlikely to be fruitful in the present context for it is too rich a subject and, unfortunately, one for which little reliable information is available for almost all systems discussed here. We will consequently attempt to illustrate the role of certain basic kinetic processes via the vehicle of a few specific modulated systems with the hope that their more general significance would be revealed in the process.

A good case to focus on is the [100] growth of GaAs–AlGaAs superlattices. It is found[24] that while the interfacial structural quality initially improves with increasing growth temperature up to about 690 °C (thought to be an extrinsic effect related to possibly Al gettering of oxygen), beyond such a temperature the interface roughness increases with further increase in temperature. Evidence for this increasing interface roughness is also found[32] in the decreasing mobility found for the AlGaAs deposited on GaAs single heterostructure (the so-called normal structures). The underlying reasons for such behavior require an understanding of the collective effect of a variety of kinetic processes influencing the growth mechanism. Timely developments in this context are the recent molecular dynamics simulations[33] of surface diffusion on the low index planes of a fcc lattice and the Monte Carlo computer simulations[34] of the growth of tetrahedrally bonded compound semiconductors along the [100] and [110] directions. Such studies offer considerable hope of revealing the underlying significance and relative importance of a variety of growth parameters and kinetic processes

in controlling the nature of the interface—at least between relatively well lattice-matched components. The notion of a kinetically controlled interface roughening for growth under far-from-equilibrium conditions has emerged from the Monte Carlo studies.[34] Much further work is necessary but can be useful in understanding relevant and unambiguous experimental observations only if further experimental work on the fundamental kinetic parameters such as the sticking coefficients, desorption rates and surface migration rates of relevance to MBE growth conditions is carried out along the lines of investigations[35–37] for As and Ga on GaAs. Greater emphasis needs to be placed on systematic follow-up work on the differences in the kinetic behavior[38] and surface reaction mechanisms[39] for different molecular species evidenced in the work[38,39] on the use of As_2 versus As_4 for growth of GaAs. Availability of accurate information on these issues will enable the molecular dynamics and Monte Carlo computer simulations to provide a greater and more reliable insight into the *collective influence* of the many individual kinetic processes on the nature of growth in both the nucleation and the continuous growth (postnucleation) regimes. The nature of reconstructions and the local behavior at the dynamic growth front should be expected to influence, and in turn be influenced by, the kinetics of epitaxial growth under the variety of growth conditions employed or potentially available. This is a virtually untackled problem. A detailed study of even a single, well specified, test system would therefore serve as a vital focal point for guiding related thinking for other material systems. Such information could be in the form of careful classification of surface structural condition and the attendant chemical conditions as a function of such growth parameters as the substrate temperature, relative and absolute fluxes of the group III and V vapor species and, in the case of alloys, the sensitivity to stoichiometry. The role of the degree of substrate–overlayer lattice mismatch in affecting the dynamics of the growth of single as well as multilayered structure remains *terra incognita*.

The kinetics of doping also remains an important area requiring similar careful and detailed investigations. The dopant segregation effects[2,3] often found in both MBE and MO-CVD require more detailed study before the relative importance of thermodynamics and kinetics may be unambiguously established, even for specific systems. It is fair to expect that dopant incorporation and segregation effects are intimately connected with the growth mechanism of the host material and the sources employed for the host species as well as the dopant. Thus, the discussion of the preceding paragraphs is pertinent to the kinetics of doping as well. Use of laser annealing can give rise to higher imcorporation limits[40] often by a factor of 10^2 and reduce segregation effects, at least in certain cases. A recent development in the effort to selectively prepare graded potential barriers is the use of MBE to implement a planar-doping concept.[41] In this doping technique, the barrier consists of a thin interior plane of dopant incorporated in an otherwise intrinsic layer. Symmetric or asymmetric barriers are produced depending on whether or not the thin interior dopant plane is centered within the confining intrinsic layer. The requirements for spatial confinement and electrical activity of dopant in this technique again stresses the need to understand segregation and incorporation effects and their relationship to the growth mechanism.

VI. CHARACTERIZATION

A comprehensive characterization of these metastable and modulated materials requires study of the structural, chemical, electronic, and optical properties together with a strong interaction between theoretical and experimental perspectives.

Structural characterization methods have traditionally involved x-ray diffraction[42] and cross-sectional transmission microscopy (TEM).[19,21,43] These new materials are particularly amenable to study by channeling methods of Rutherford backscattering spectroscopy (RBS)[44] as well as cathodoluminescence.[43] With recent advances in resolution, double crystal x-ray diffractometers can now be used to study variations of structure and lattice constant within the component films of a multilayer system.[42] Study of the crystal perfection of the resulting structure as a function of differing growth condition and techniques permits correlation of defect densities with the method. TEM and cathodoluminescence studies of GaAlAs/GaAs superlattices have demonstrated[43] the existence of interface roughening with increasing temperature discussed earlier, as well as the observation of interfacial gettering of impurities.[19,45] For a variety of chemical reasons, it is conceivable that surface segregation of impurities to the growth interface could lead to a constant surface contamination layer which would not be buried by homogeneous film growth. The growth of a heterostructure with interfaces between chemically distinct material could provide an interface chemical potential and the possible intermediate environments to reactively trap impurities at the interface. The sequential enhancement of layer morphology in superlattice structures has been demonstrated[45] and future studies will certainly focus on the interrelationship of impurities and film quality. Ion channeling along different crystalline axis of a solid provides important information on lattice geometry, the nature of defects, and the details of the interfacial structure.[44] This analysis of InAs–GaSb and Ge–GaAs superlattices has demonstrated the high degree of structural perfection achieved in these materials and has pointed out the existence of unique interfacial structures which appear to develop in response to the chemical nature of the interfacial discontinuity. Amongst the several optical and electrical techniques employed for characterization, photoluminescence and low field Hall mobility are the more common ones. The photoluminescence linewidth at low temperatures is taken to be a measure[24] of the interfacial quality but cannot, without detailed theoretical development, separate the contributions from varying degrees of interface roughness that might exist at different interfaces in multilayered structures. Some evidence for such differences in interfacial quality is provided by the Hall mobility measurements[32] on normal and inverted GaAs/AlGaAs single interface heterostructures.

The quasi-two-dimensionally confined electronic states of most relevance in single and modulated structures depend upon the change in the crystal potential across the inter-

face(s) involved.[46] No reliable theory for self-consistently calculating such a change is presently available. Experimental determinations of the equivalent quantity of operational use—the band edge discontinuity—have been undertaken but invariably rely upon either fitting to some optical property (such as absorption)[47] or involve the independently untested notion[48] of the core levels following the band bending of the valence and conduction band edges up to the interface. A complication, with significant consequences for the properties of multilayered structures involving ultrathin layers, is the possible difference between the band edge discontinuity of material A deposited on B and vice versa.[48] If substantiated, this evidence would reflect, once again, the central role played by the growth conditions and mechanisms, rendering the A on B and B on A interfaces sufficiently different in their physical and chemical nature.

Investigations of the single particle and collective properties of the quasi-two-dimensionally confined carriers arising from the band edge discontinuity has, of course, been an area of active investigation for the past decade.[49] These investigations range from studies of the quantum Hall effect and quantum Wigner crystallization to those focusing on properties with a more immediate relationship to device prospects. The latter offer the natural transition from growth aspects, emphasized heavily at the MMSS conference, to the high speed and/or high frequency devices one looks forward to. Much of the transport work hitherto concerns itself with motion parallel to the interface. Two results involving observation of new phenomena are reported in these proceedings. These are (i) the first observation[50] of the deHaas–van Alphen effect in a two-dimensionally confined electron gas, and (ii) the observation[51] of the theoretically predicted[52] acoustic plasmon mode in a multiple quantum well structure. The latter was achieved via the use of inelastic light scattering technique. A variety of studies of the two-dimensional (2-D) electron gas are possible via light scattering techniques and we should expect such work to be carried out further. Improvements in the low field electron mobility in GaAs/n-AlGaAs modulation doped heterostuctures (HEMT) continue to be made,[53] the liquid helium value now approaching[54] 2×10^6 V/cm^2 for the very best MBE samples. Theoretical analysis of the role of modulation doping and spacer layer(s) in single and multi-interface structures in influencing the mobility needs to be carried out with a much greater degree of sophistication than presently available.[55,56] Only then may one have a meaningful understanding of the inherent limits placed on the low temperature mobility by the remote ion scattering and interface roughness scattering. It is worth noting that though the high field transport studies found little representation at the MMSS conference, it is an area of active work deserving of even greater attention.

Some work on carrier transport normal to the interfaces is beginning to emerge[57] but the subject offers much potential for interesting characteristics and effects. Tunneling effects and real-space charge-transfer processes[58] require particular attention, for they can act as both characterization tools for obtaining information on the atomistic nature of the interfaces, as well as physical effects which may be exploited for device applications. The infrared detector studies[59] based on electron emission from multiple quantum well structures, and the enhancement of electron impact ionization in multilayer avalanche photodiodes[60] are investigations which will undoubtedly be pursued further. Investigations of the dielectric function of multilayered structures has been sorely lacking given their significance for optical devices. Techniques such as spectroscopic ellipsometry[12] offer much potential for generating such information, but will not provide the understanding sought unless progress is made on the theoretical side as well.

Little has so far been unambiguously accomplished in understanding the origin and nature of point defects and their complexes at and near interfaces. This is particularly true of the formation of native point defects and their complexes during far-from-equilibrium growth of thin films and the formation of interfaces, although some preliminary studies have been carried out.[61] Some elementary studies of the confinement effect on bulk shallow impurities and their consequences have begun,[62] but offer many challenging problems of scientific and technological importance. The situation with regard to deep levels in modulated structures remains even less investigated[63] and deserves greater effort. Among the variety of characterization techniques employed, the use of light scattering techniques for investigations of the lattice dynamics and electronic states has hitherto not been as prevalent as the potential of such techniques might lead one to expect. One might therefore expect a greater use and development of such techniques for study of the phonon modes and defect induced levels in modulated structures.

VII. CONCLUSION

The evidence presented in the preceding section indicates that the study and synthesis of metastable and modulated semiconductor structures constitutes an area which should prove particularly fruitful for both scientific and technological research. The synthesis or fabrication of these unique materials provides a number of opportunities for detailed theoretical and experimental investigations of the fundamentals of growth. The increasing use of MBE preparative methods make available the dynamic growth interface for study, characterization, and manipulation via a variety of technological approaches. These unique materials provide new opportunities for characterization and basic studies of their structural, chemical, electronic, and optical properties. The potential for creating a wide class of new materials based on semiconductor/semiconductor, semiconductor/insulator, and semiconductor/semimetal single and multiple interface structures with and without lattice matching constraints allows new approaches to microelectronic device design, development, and application. Extreme dimensional control of dopants add still other degrees of freedom to these material and experimental systems. Finally, the interdisciplinary aspect of this research, requiring the interaction of theorists and experimentalists representing chemistry, solid state physics, surface science, crystal growth, material science, and device physics and engineering, will provide a particularly stimulating synergism for general progress in the area of electronic materials.

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